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Abstract: Network coding mechanisms, such as COPE, can improve network throughput effectively in Wireless Mesh Networks (WMN). While the Hybrid Wireless Mesh Protocol (HWMP) is suitable for WMN, its extension with COPE does not provide any added benefits; specifically, HWMP cannot establish paths with more coding opportunities. As a result, the advantages of network coding cannot be exploited sufficiently. This paper proposes improvements upon HWMP with a new, network Coding-Aware routing protocol (CAHWMP) for WMN. In the CAHWMP protocol, we propose a coding criterion based on data streams to devise an algorithm for actively detecting coding opportunities during path discovery. CAHWMP subsequently establishes paths using the coding-aware routing metric, which can balance channel resource consumption and the gain due to sharing resources introduced by network coding. Simulation results show that CAHWMP can establish paths with more coding opportunities; as a result, it improves network performance such as network throughput.

Key words: wireless mesh network; network coding-aware; Hybrid Wireless Mesh Protocol (HWMP); COPE mechanism; coding criterion

1 Introduction

A Wireless Mesh Network (WMN) is a multi-hop network with wide coverage, large network capacity, fast access speed, and low deployment cost. It is a novel scheme to solve the bottleneck challenges of the last kilometer[1]. The design of routing protocols is one of the key issues in WMN. The Hybrid Wireless Mesh Protocol (HWMP) is the default routing protocol for WMN in the IEEE 802.11s standard[2]. Unlike traditional proactive and reactive routing protocols, HWMP is a hybrid WMN routing protocol that expands and combines reactive routing with a proactive tree structure.

HWMP takes full advantage of the two kinds of routing protocols, which results in not only shorter delays in path establishment but also less control overhead. Moreover, HWMP uses a space-time link metric, which can reflect link quality better than a hop count metric. This makes HWMP more suitable for WMN with diverse topologies and link qualities, compared with routing protocols such as Ad hoc On-demand Distance Vector (AODV) or Destination-Sequenced Distance Vector (DSDV).

Since network coding was first proposed by Ahlswede et al.[3] in 2000, it has been a hot topic in the communications field and has been researched extensively[4, 5]. Network coding techniques break through the traditional store and forward transmission mechanism, and efficiently make use of the broadcast capability in the physical layer of the wireless channel in order to improve bandwidth efficiency and decrease energy consumption. Non-destination nodes store the sensed data while not discarding it, and subsequently accomplish network coding or decoding by cooperating with other nodes. Destination nodes decode the encoded packets to get the needed data. Network coding increases the amount of information included in a single transmission, yet can improve network throughput,

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which makes it an effective way to approach the theoretical limit of network transmission capacity. The features of WMN together with its need for high throughput make it suitable for utilizing network coding techniques.

COPE[6] is a mechanism that applies network coding in actual wireless unicast communication networks. COPE is based on the principle of opportunism. Nodes first sense the wireless link opportunistically to get status information of neighbor nodes. Subsequently, it performs opportunistic encoding of the information. While the HWMP protocol is suitable for WMN, its extension with COPE does not provide added benefits; specifically, it cannot create paths with more coding opportunities. As a result, the advantages of network coding cannot be fully exploited. Therefore, there is a need for research on network coding aware protocols that can utilize the COPE mechanism, and as a consequence, improve network performance.

In this paper, we propose CAHWMP — a network Coding-Aware routing protocol for wireless mesh networks based on HWMP. We also simulate and analyze its performance.

The rest of the paper is organized as follows. In Section 2, we review related work. In Section 3, we introduce COPE and the notion of network coding awareness. In Section 4, we propose the CAHWMP. In Section 5, we describe path establishment with CAHWMP. In Section 6, we simulate CAHWMP and compare its performance with HWMP and COPE-HWMP. Finally, in Section 7, we conclude the paper.

2 Related Work

Research on network coding in WMN is still at an exploratory stage. COPE studies the implementation of network coding in wireless network protocols. It integrates network coding into the protocol stack and makes it work with high layer protocols seamlessly. COPE improves the throughput of wireless networks significantly. COPE provides a good scheme for applying network coding with unicast communication in WMN. Consequently, COPE has been an active area of research[7–9].

The benefits of COPE relative to current data forwarding mechanisms are analyzed in Ref. [10]. Specifically, coding opportunity, overhearing probability, and probability threshold of a network node with the COPE mechanism are analyzed, which then provide a basis for analyzing performance of COPE in the network layer. COPE is applied in Ref. [11] to achieve reliable multicast in wireless networks. The main idea is to combine retransmission with network coding. Lost packets are encoded by COPE before transmission and correctly received packets are used to decode. As a result, with a single transmission, multiple receivers can recover their lost packets. Re-CoZi is based on one hop coding[12]. It enables robust XOR coding with echo-feedback packet reception together with decoding acknowledgement. Performance analysis shows that Re-CoZi can maintain bandwidth efficiency, limit delay introduced by network coding, and improve the reliability of coding in lossy communication transmissions.

A Network Coding-based Probabilistic Routing (NCPR) scheme[13] can alleviate the broadcast storm problem and improve bandwidth efficiency. In NCPR, each neighbor node encodes received packets with its sensed packet using XOR network coding, and transmits the coded packet with a certain probability. Simulation results show that it can provide better energy efficiency and reliability. Opportunistic Network Coding (ONC)[14] uses different strategies to select multiple lost packets in order to encode and then retransmit them. It improves throughput in broadcast transmission by recovering lost packets from the coded packet. Simulation results show that ONC can reduce broadcast transmission bandwidth and save energy effectively in different wireless channel models.

COPE can improve network throughput and save energy costs. However, the notion of opportunism causes it to passively wait on existing paths for coding opportunities. If there are none or only a few nodes with coding opportunities in the path established by the routing protocol, then COPE has no impact on enhancing network performance. Therefore, at present research on coding-aware protocol is deployed gradually.

The COPE mechanism can be improved, as in Ref. [8], by encoding the node with more input links than output links. Nodes with more output links than input links can transfer without coding. This can reduce redundant coding overhead. A Distributed Coding-Aware Routing protocol (DCAR)[15] uses a coding-aware routing metric to achieve an efficient routing mechanism; this helps find potential coding opportunities. The generalized coding conditions are defined to find coding opportunities after two hops. DCAR can lead to sub-optimal paths since its routing metric is not isotonic, and a routing metric ETX-CA is proposed in Ref. [16]. Coding perception is introduced and a unique mapping process is designed to map a real wireless network to a virtual one.

A routing metric, Heuristic Path Metric for Coding and Load-balancing (HPMCL), which considers coding opportunity, network load, and expected transmission times comprehensively, is proposed in Ref. [9]. A routing protocol HLCR is presented in order to discover coding opportunity and balance network load effectively. The theoretical formula of computing throughput with network coding in any wireless network topology and any concurrent unicast transmission mode is derived in Ref. [17]. It provides the optimal path for data packets to reach the destination node based on maximizing network throughput. Each node in the network can balance data traffic and avoid wireless interference with coding opportunity.

A network coding protocol, OASIS, is presented in Ref. [18]. It not only inherits two features of opportunistic sensing and opportunistic coding from COPE, but also introduces opportunistic information dissemination. A node encodes as many packets as possible, and increases data packet pools for neighbor nodes to improve the probability of future coding. Simulation results show that OASIS can improve the network throughput by about 1.4 times that of traditional unicast, and by about 1.2 times that of COPE. Coding aware routing protocols have some weakness with real-time delivery on lossy links. A Coding-Aware Real-Time Routing protocol (CARTR) is presented to solve the problem[19]. It schedules coded and uncoded data packets on a link by precedence. Experiments reveal that CARTR improves throughput by about 20%. A coding-aware deployment strategy is presented in Ref. [20], which creates opportunity for network coding at aggregate sensor nodes. The deployment strategy can effectively avoid multilink failures in the network. Sensed data of leaf nodes is transmitted after getting encoded by intermediate nodes, which reduces packet redundancy.

Existing research on network coding aware routing protocols and algorithms considers increasing coding opportunities or maximizing network throughput, however, the study of coding opportunity detection and path selection based on coding gain is limited.

3 Network Coding Awareness

The primary idea behind adding network coding-awareness to routing protocols is to detect coding opportunities actively in the process of routing discovery, and to use network coding-aware routing metrics to establish paths with more coding structures. This enables more coding opportunities to be created in order to make better use of COPE.

If data streams follow the paths, in accordance with any one coding structure for COPE, then there exists an opportunity for coding, and the COPE mechanism can be utilized. Consider the X-type coding structure shown in Fig. 1. A source node S_1 sends a packet p_1 to its destination D_1, and simultaneously another source node S_2 sends a packet p_2 to a destination node D_2. Node v is the transferring node. Assume that node D_1 can get packet p_2 through carrier sense and D_2 can overhear p_1. If node v is aware that nodes D_1 and D_2 have sensed packets p_1 and p_2, respectively, then it XOR-encodes the two packets and gets the encoded packet $p_3 = p_1 \oplus p_2$. Subsequently, node v transmits p_3 through one transmission.

If D_1 receives the packet p_3, it performs the decoding operation $p_2 \oplus p_3$ to obtain packet p_1. In the same way, D_2 gets the packet p_2 by decoding $p_1 \oplus p_3$, after it receives p_3. In this way, the amount of data transmitted by three packets using the COPE mechanism is same as the amount of data transmitted by four packets without using network coding. Thus, network throughput increases by 33.3%.

After the paths are established with the routing protocol, the data packets can be encoded with COPE depending on the coding structures formed by the paths. Therefore, the routing protocol determines the chances of COPE's ability to code directly. We illustrate this by constructing a simple network using several nodes as shown in Fig. 2. In the network shown, there exists a path (6, 5, 4) formed from a source node 6 through node 5 to destination node 4. If another source node 1 sends data to a destination node 3, it first needs to establish a

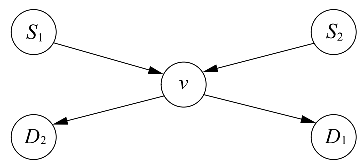

Fig. 1 X-type coding structures for COPE.

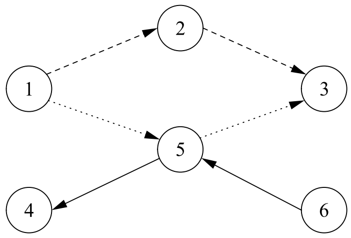

Fig. 2 Network coding aware idea.

path from node 1 to node 3.

In the routing discovery process of a common routing protocol, the opportunities for coding cannot be detected actively, and routing metrics are used without coding-awareness. As a result, a path (1, 2, 3) may be established. Since the two paths cannot form a coding structure for COPE, and the routing protocol does not create any coding opportunity, the COPE mechanism is unable to provide any benefit. However, if a network coding-aware routing protocol is used, there is a coding opportunity to be detected actively with a coding aware routing metric in routing discovery. This allows for the establishment of the path (1, 5, 3). This path can constitute an X-type COPE coding structure with path (6, 5, 4), and a chance of coding is made at node 5; consequently COPE can be applied to enhance network performance.

4 CAHWMP Protocol

In this section, we propose a coding criterion based on data streams in paths. This criterion is used to detect coding opportunities during routing discovery of the CAHWMP protocol. We design a network coding-aware space-time link metric, NCCa, which can be used to establish paths.

4.1 Coding criterion based on data streams

To ensure that each next-hop node decodes the coded data packet and gets the desired packet, we define the coding criterion using COPE at node v as follows. To transmit n packets $p_1, p_2, \cdots, p_n$ individually to n next-hop nodes R_1, R_2, $\cdots$, R_n, each node R_i saves all the other $n-1$ packets p_j ($j = 1, \cdots, n, j \neq i$), such that node v can XOR-encode the n packets. This coding criterion is based on the data packets; however, data transmission does not begin before path establishment. As a result, this criterion is not suitable for coding judgment in path discovery. In order to apply coding judgment in the path discovery process of CAHWMP, we propose a new coding criterion based on data streams in paths.

As can be seen from the coding criterion and coding structure of COPE, in a path of node v, if a next-hop node gets a packet p, which node v transfers, before node v receives it or at the same time as node v, then the node must be a previous-hop node that transmits the packet p or its neighbor. Therefore, to ensure that the next-hop node in the path of each data packet has saved all the other packets to encode, the node should be a previous-hop node or its neighbor in the paths of these data packets.

Assume that there are a number of data streams passing through node v using different paths. On these paths, n pairs of previous-hop and next-hop nodes of node v form n hop-pairs, denoted by (prev_i, next_i), $i = 1, 2, \cdots, n$. If packets in these data streams can be encoded at node v with COPE, then these n hop-pairs form a coding set. A single hop-pair can build a coding set independently. As a result, we present a criterion of coding judgment based on data streams.

Criterion of coding judgment based on data streams:

Packets in data streams can be encoded with COPE at node v, namely, the corresponding n hop-pairs (prev_i, next_i) can form a coding set, if and only if the n hop-pairs satisfy the following conditions: Any one next-hop node next_i ($i = 1, 2, \cdots, n$) in a hop-pair is either a previous-hop node prev_j in the other $n-1$ hop-pairs ($j = 1, 2, \cdots, n$ and $j \neq i$) or a neighbor of the node prev_j. The expression is

$$(\text{next}_i == \text{prev}_j) \vee (\text{next}_i \in \text{NB}(\text{prev}_j)),$$
$$i = 1, 2, \cdots, n;\ j = 1, 2, \cdots, n \text{ and } j \neq i \qquad (1)$$

where $\text{NB}(\text{prev}_j)$ stands for the set of neighbors of the previous-hop node prev_j.

In CAHWMP protocol, the required information for the coding criterion about data streams on transmitting and the corresponding hop-pairs at node v can be acquired by searching the routing table maintained by node v. The routing table is composed of a number of routing entries to different destination nodes. In each route entry, destination address, destination sequence number, and destination PREQ ID are used to uniquely identify a path.

4.2 Network coding aware link metric NCCa

In the IEEE 802.11s standard, a default link metric, Ca, based on space-time, is defined, which is used to calculate channel resources consumed in data transmission. Compared with a hop count metric used usually in mobile ad hoc networks, the Ca metric is more suitable for wireless mesh networks with complex network topologies and variable link quality. Ca can be calculated using Eq. (2). The path metric is the sum of link metrics on the path.

$$\mathrm{Ca}=\left(O_{\mathrm{Ca}}+O_{\mathrm{p}}+\frac{B_{\mathrm{t}}}{r}\right)\frac{1}{1-e_{\mathrm{fr}}} \tag{2}$$

Here the channel access overhead O_{Ca}, protocol overhead O_{p}, and length of normal test frame B_{t} are all constants. Their values are determined by adopting IEEE 802.11 transmission technology. r denotes the transmission rate (in Mbit/s) of a test frame in the WMN. Frame error rate is denoted as e_{fr}.

The link metric Ca only reflects the amount of channel resources consumed while transmitting data frames on the link. If the COPE mechanism is applied in data transmission, and several packets are encoded together into a single packet sharing the same link resource, then Ca does not reflect the benefit of channel resource sharing. Therefore, we propose a network coding aware space-time link metric NCCa in the CAHWMP protocol, which takes channel resource consumption and the gain of resource sharing introduced by network coding into consideration comprehensively.

In the network coding mechanism, if several packets are encoded at a certain node, then the encoded packet reaches all the destinations through a single transmission. The relationship between the channel resource consumption in transmitting a single encoded packet and each original data packet to be encoded within the next-hop link can be described by Theorem 1.

Theorem 1 If there are n original data packets that can be encoded at a node, the amount of resource consumption in the next-hop link of each packet is assumed to be $\mathrm{Ca}_1, \mathrm{Ca}_2, \cdots$, and Ca_n individually. The channel resource that is consumed by the encoded packet is the maximum across all the links, $\max\{\mathrm{Ca}_1, \mathrm{Ca}_2, \cdots, \mathrm{Ca}_n\}$. That is to say, each packet to be encoded can share the maximal amount of link resources to transmit.

Proof Without loss of generality, consider an example of two packets, p_1 and p_2, to be encoded. Assume that the next-hop link resource consumption of each packet is Ca_1 and Ca_2, respectively, where $\mathrm{Ca}_1 < \mathrm{Ca}_2$. The encoded packet can reach each next-hop node of the two packets through different links by broadcast. Hence, the channel resource consumption of the encoded packet depends on the next-hop link with greater resource consumption. Here the link consumption is Ca_2. Therefore, the channel resource consumption that can be shared by the encoded packet consisting of the two original packets is $\max\{\mathrm{Ca}_1, \mathrm{Ca}_2\}$. By analogy, the channel resource consumption that can be shared by an encoded packet containing n original packets is $\max\{\mathrm{Ca}_1, \mathrm{Ca}_2, \cdots, \mathrm{Ca}_n\}$. ■

Also consider the X-type coding structure shown in Fig. 1. The source node S_1 transmits data to the destination node D_1 through path (S_1, v, D_1), and node S_2 transmits node D_2 through path (S_2, v, D_2). The packets are encoded at node v, and the encoded packet is transmitted to nodes D_1 and D_2. Suppose that path (S_1, v, D_1) is an existing path transmitting data streams. Using routing discovery of the CAHWMP protocol, node S_2 can establish a path with coding opportunity to destination D_2, passing through node v. If D_2 receives the PREQ packet, it can check this packet to determine if it can act as a next-hop node; if so, there is a chance of coding at node v. The channel resource consumption Ca(v, D_1) on the other next-hop link (v, D_1) can also be obtained.

According to Theorem 1, the amount of resource consumption to be shared by the original packets is max{Ca(v, D_1), Ca(v, D_2)}. If Ca(v, D_2) $\leqslant$ Ca(v, D_1), then the transmission of a coded packet can fully share the cost on link (v, D_1), namely incidental transmission. Therefore, the resource consumption on link (v, D_2) can be regarded as 0 after network coding. Else if Ca(v, D_2)$>$Ca(v, D_1), then with network coding, the resource consumption on link (v, D_2) will be calculated by Ca(v, D_2)$-$Ca(v, D_1). Consequently, we can present the definition of link metric NCCa on normal conditions.

Definition 1 When there are N links passing through a node i, the metric NCCa(i, j) to be used in route discovery to search a link *l:(i, j)* on path L is calculated as follows:

$$\mathrm{NCCa}(i,j)=\begin{cases}\mathrm{Ca}(i,j), & \text{if there is no coding opportunity at node } i;\\ \mathrm{Ca}(i,j)-\min\begin{pmatrix}\mathrm{Ca}(i,j)\\ \max(\mathrm{Ca}(i,n_k))\end{pmatrix}, & \text{if there is an coding opportunity at node } i\\ (k=1,2,\cdots,N, n_k\neq j) & \end{cases} \tag{3}$$

where n_k stands for N next-hop nodes of the original packets, except node *j*, to be encoded at node *i*. Ca(i, j)

is the resource consumption on link l. Ca(i, n_k) denotes the resource consumption of each next-hop link.

In Eq. (3), if there is no chance of coding at node i, then NCCa(i, j) is equal to its usual resource cost Ca(i, j). Else, if there is an opportunity of coding at node i, and Ca(i, j) on the link l is less than the maximal resource cost of the other N next-hop links, then NCCa(i, j) equals 0. Otherwise, if there is also a chance of coding at node i, and moreover, Ca(i, j) is the maximum of all the N+1 next-hop links of the packets to be encoded, then NCCa(i, j) is equivalent to Ca$(i, j)-$ max {Ca(i, n_1), Ca(i, n_2), $\cdots$, Ca(i, n_N)}.

Definition 2 The metric of path L is the sum of all metrics of links on this path:

$$\text{NCCa}_L = \sum_{l \epsilon L} \text{NCCa}(i, j) \tag{4}$$

To get the required space-time link metric Ca on a link to its neighbor for calculating NCCa, a node should maintain a neighbor node receiving table, in which the address of neighbor nodes, neighbor reports, and Ca are stored. This information is made available for COPE coding.

5 Path Establishment

Three processes are included in path establishment of the CAHWMP protocol: path discovery, path reply, and path maintenance.

5.1 Path discovery

In wireless mesh networks, a node is called a Mesh Point (MP). When a source MP needs to send data to a destination MP, it first checks its routing table to see whether there is an available route to the destination. If there is no route, the source MP should start a path discovery process to the destination MP. First, it broadcasts a path request packet PREQ. In the PREQ of the CAHWMP protocol, two fields of Add and Previous-hop MP address are appended. The Add field stores the ADD set, which is the output running the coding opportunity detection algorithm as shown in Fig. 3. Before broadcasting, the fields of Hop Count, Metric, and Add are all initialized to 0. The MAC address of source MP is written in the Last Hop Address field.

In the coding opportunity detecting algorithm, if an intermediate MP (e.g., node v) receives a PREQ packet, it will operate as follows:

(1) Increment the value of the Hop Count field by 1.

(2) Decrement the value of the TTL field by 1.

Input: Routing table of node v, Neighbor receiving table of node v and PREQ packet
Output: The set ADD of dualistic group{n_j, max(Ca)}
Procedure:
Initialize ADD = NULL
Check the routing table to obtain the n hop-pairs (prev$_i$, next$_i$) (i = 1, 2, $\cdots$, n) corresponding to data streams;
For (the n hop-pairs) do
    Full permute and combine these hop-pairs, the number of pairs is increased from 1 to n by degrees, to form $2^n - 1$ sets composed by the hop-pairs;
    For (the $2^n - 1$ sets of hop-pairs) do
        Judge if this set can constitute a coding set according to the coding criterion based on data stream;
        If (this set is a coding set) then
            Add it to the set named SET;
    End for
End for
Check the PREQ packet to get the previous hop MP v_{prev};
Check the neighbor MP receiving table to get k neighbor MPs n_j (j = 1, 2, $\cdots$, k) of node v;
For (the k neighbor nodes) do
    Constitute hop-pairs (v_{prev}, n_j) (j = 1, 2, $\cdots$, k);
End for
For (the k hop-pairs (v_{prev}, n_j) (j = 1, 2, $\cdots$, k)) do
    For (m coding sets in SET) do
        If (the hop-pair(v_{prev}, n_j) cannot satisfy the coding criterion to encode with data streams from each other hop-pairs in SET) then
            Delete it from SET;
    End for
    Take the coding set which has the most hop-pairs from SET and obtain information about every next-hop node from the set;
    Check the neighbor receiving table to get Ca of every next-hop node and select the maximum value max(Ca);
    ADD = ADD ∪ {n_j, max(Ca)}
End for
Return ADD

Fig. 3 Coding opportunity detecting algorithm.

(3) Update the Metric field as follows. It reads the Add field. If the field is NULL, or this MP is not within the dualistic group sets {n_j, max(Ca)}; then there is no chance of coding at the previous-hop node when this MP is selected to be the next-hop node. Here n_j denotes a next-hop node with coding chance. max(Ca) represents the maximal link overhead of other next-hop routes with coding chances. The link metric NCCa can be calculated by Eq. (3).

However, if the MP is one of the nodes in the dualistic group{n_j, max(Ca)}, then there is a chance of coding. And the value of relevant max(Ca) is taken from the

Add field to calculate NCCa. Subsequently, the value of NCCa is added to the Metric field.

(4) Start up the coding opportunity detection algorithm. First, it writes the ADD set to the Add field. Subsequently, it writes the value of max(Ca) to the route entry field in the routing table.

(5) Create or update the reverse path to the source MP based on information carried in PREQ. If there is no route from the intermediate MP to the source MP, it will create a route to the source. If it already has a route to the source MP, the intermediate MP will check for an update. If the sequence number in the received PREQ is larger than the existing one, it will update the current path. Else if the received sequence number is equal to the existing one, but the Metric in PREQ is better, then the MP will also update the current path.

(6) Update the Last Hop Address field. It writes the MAC address of this MP.

(7) Continue to forward the PREQ packet to neighbor MP if this MP is not the destination MP, and the value in the TTL field of the PREQ is larger than 0. Similar to the HWMP protocol, loop prevention in CAHWMP is done using sequence numbers. If the PREQ ID and source MP address in the PREQ packet are both the same as those in the MP, then the packet will be discarded.

5.2 Path reply

It is prescribed in CAHWMP that after the destination MP receives the first PREQ, if it receives several PREQ packets in a short delay time T, then it chooses the one with the minimum NCCa in the Metric field to generate the path reply packet PREP. If the sequence number in the PREQ is equal to that of the destination MP plus 1, then the destination MP should add 1 to its sequence number before generating the PREP packet. Otherwise, it does not change its sequence number. Afterwards, the destination MP inserts its sequence number into the corresponding PREP field, and sets both the Hop Count and Metric fields to 0. Afterwards, the PREP packet is unicast to the previous-hop MP along the reverse path till it reaches the source MP.

After receiving the PREP packet, the intermediate MP establishes the path to the destination MP formally. First, it adds 1 to its Hop Count field. Next it takes the value in the maxCa field of the route entry and calculates the NCCa of the previous hop link. Subsequently, it adds it to the Metric field of PREP. Finally, it writes the Hop Count and Metric fields of the route entry. It continues to forward this PREP to the previous hop MP, and does the same update till it reaches the source MP. Once the source MP receives the PREP, it updates the route entry to the destination MP in the same way and then destroys the PREP. In this way, the path from the source MP to the destination MP is established, and the source MP starts to send data.

5.3 Path maintenance

Alternate path is an optional way of route maintenance in the HWMP protocol, but the CAHWMP protocol does not enable this mechanism. Since the PREQ packet is sent periodically to establish alternate paths from the source MP to the destination MP using the same process and stored in the route table, this causes an increase in the consumption of bandwidth and resources.

When an MP on an active path fails to transmit a data packet after finite retransmission times, this means that the link from this MP to its next-hop is disconnected. This results in a path error message, PERR, to be sent to maintain path. The destination MP of this path is called the unreachable destination MP. The PERR packet records the number, MAC address, and sequence number of unreachable destination MPs.

Before sending the PERR packet, the sequence number of all unreachable destination MPs in the route table is incremented by 1 and their routing entries are marked as invalid. Subsequently, the PERR packet is sent to the previous-hop MPs in routing entries corresponding to all the unreachable destination MPs. The previous-hop MP that receives the PERR packet checks its routing table to see if there are any destination addresses in the list of unreachable destination MPs. If there are none, then this PERR is discarded. Otherwise, the sequence number of the destination MP in the route entry is updated to be the corresponding sequence number in PERR, and the route entry is marked invalid.

A PERR packet is generated according to new unreachable destination MP. The unreachable destination MP in the new PERR is a subset of that in the original PERR. PERR packets continue to be sent to previous-hop MPs in the routing table corresponding to the unreachable destination MP. When the source MP receives the PERR, it updates the sequence number of the unreachable destination MP similarly; it marks the route entry invalid and restarts path discovery process to the destination MP.

6 Simulation and Analysis

The network simulation software, NS2, is used to simulate the performance of the CAHWMP protocol. It is compared with the HWMP and COPE-HWMP protocols. Here COPE-HWMP refers to the use of the HWMP protocol together with COPE.

6.1 Scene set

In the simulation, a random network topology is used to simulate an analog WMN. 36 stationary nodes are randomly distributed in an area of 1000×1000 m^2. The effective transmission distance between nodes is 300 m. Simulation time is set to be 200 s. The MAC layer is set to use IEEE 802.11b standard, and channel capacity is 2 Mbit. The packet loss rate between any two nodes is randomly set. Constant Bit Rate (CBR) data streams are set in the network transmission, whose packet size is 512 Byte. The source MP generates 20 CBR packets per second. By simulation, performance of network throughput, average end-to-end delay, and packet delivery rate are investigated in the mesh network with a different number of data streams. The number of data streams is increased, in intervals of two, from 2 to 28. Simulation results are taken from an average of 30 experiments.

6.2 Simulation results

Figure 4 shows the graph of network throughput following the change in the number of data streams using the three protocols. When the number of data streams in the network is less than four and the network load is quite low, almost all data packets are able to reach destinations successfully. Therefore, the performance of network throughput shows no obvious differences under the three circumstances. However, when the number of data streams adds up to more than six, packets loss occurs due to network congestion; as a result, the increase in throughput using the three protocols slows down. As COPE is enabled in the COPE-HWMP protocol, there are some coding chances to relieve network congestion. Hence, packet loss rate is reduced and the throughput of COPE-HWMP is higher than HWMP.

However, the network throughput of the CAHWMP protocol is higher than that of COPE-HWMP. This is because in CAHWMP, network coding can be performed actively, and paths with more coding opportunities can be chosen in path establishment. Consequently, there are more coding chances in CAHWMP than in COPE-HWMP. Network congestion is also alleviated more efficiently to reduce packet loss rate. With the addition of data streams, we observe greater increase in throughput using CAHWMP when compared with COPE-HWMP. The main reason is that in the establishment of each new path, the CAHWMP protocol generates more coding opportunities than COPE-HWMP. Comparing the average network throughput of the three protocols, CAHWMP is 12.7% higher than COPE-HWMP, and 28.3% higher than HWMP.

Figure 5 shows the graphs of average end-to-end delay along with the changing number of data streams. As seen in Fig. 5, as the number of data streams increases, the network load also correspondingly increases. This also results in prolonging the time that data packets need to wait in the interface queue until the queue gets saturated, after which the end-to-end delay trends to be stable. The application of COPE allows some packets in the sending queue to be encoded into one packet, which reduces their waiting time. Therefore, CAHWMP and COPE-HWMP can both reduce their average end-to-end delay significantly.

Comparing the average values of end-to-end delay, CAHWMP results in a 26.9% decrease when compared with HWMP. In addition, it is 13.6% less than COPE-HWMP. This is because the link metric NCCa takes

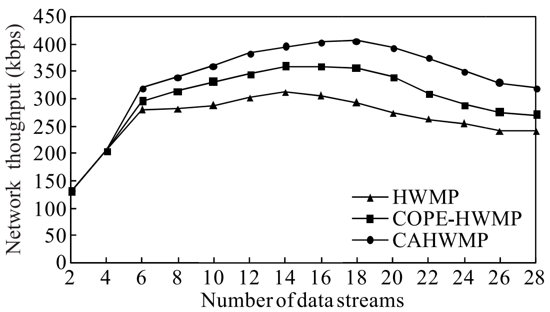

Fig. 4 Network throughput.

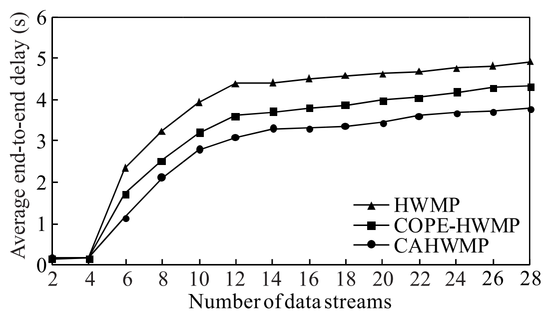

Fig. 5 Average end-to-end delay.

both channel resource consumption and the gain due to sharing resources introduced by network coding into account. Therefore, coding chances in CAHWMP is greater than that in COPE-HWMP. This also enables the average waiting time of packets to be decreased, which can reduce end-to-end delay.

The performance of packet delivery rate is shown in Fig. 6. With the increase in data streams, network congestion gets more and more aggravated, which correspondingly results in an increase in lost packets; hence, packet delivery rate gradually decreases. The trend of the three curves is consistent. In the CAHWMP and COPE-HWMP protocols, the application of COPE alleviates network congestion, and reduces the numbers of lost packets; as a result, their curves for the data delivery rate are above that of HWMP.

Comparing the two protocols, the curve of CAHWMP is still higher than COPE-HWMP. This is because the CAHWMP protocol has more coding opportunities and uses paths for delivering packets more effectively, which can further reduce congestion and the number of lost packets. Comparing the average packet delivery rate in the three circumstances, the value for CAHWMP is 8.7% higher than HWMP and 4.3% higher than COPE-HWMP. From the simulations, we can see that the CAHWMP protocol has better network performance than the other two protocols.

7 Conclusions

We propose a network coding-aware routing protocol, CAHWMP, based on HWMP in this paper. First, we present a coding-aware routing metric NCCa, which improves the space-time link metric Ca of HWMP. NCCa takes into account link resource consumption and channel sharing gain brought by network coding collaboratively, which can reflect the impact of network coding on channel resource cost. Next we present a new coding criterion based on data streams in paths. Subsequently, we propose a coding opportunity detection algorithm using this criterion. The algorithm is used in path discovery of CAHWMP in order to actively detect network coding chances, and to establish paths with more coding opportunities based on the NCCa metric. Comparing CAHWMP, COPE-HWMP, and HWMP protocols through simulation, we verify that the CAHWMP protocol can detect greater coding chances, further improve network throughput, reduce end-to-end delays, and enhance packet delivery rate.

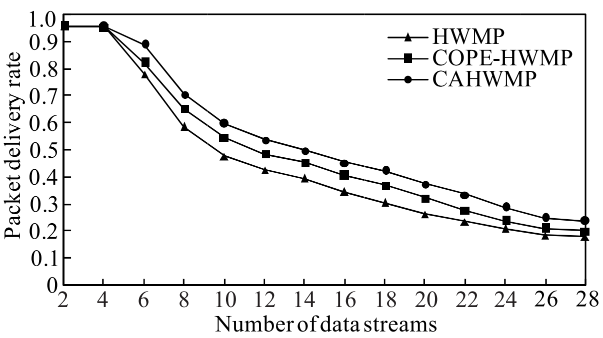

Fig. 6 Packet delivery rate.

Acknowledgements

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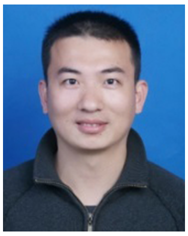

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